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High resolution spectroscopy of Brown Dwarfs in Taurus

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Abstract. We present high resolution optical spectroscopy of three candidate members of the Taurus-Auriga star forming region. Based on the spectral type, the strength, profile and width of the Hα line, the detected lithium at 6708 Å, the location of these objects in a H-R diagram and the comparison with similar objects belonging to young stellar associations, we determine that they are bona fide members of the SFR, with about $\sim$3 Myr, have masses at or below the substellar limit and, at least in one case, there is active accretion from a circum(sub)stellar disk. This result suggests that high mass brown dwarfs go through a Classical TTauri phase and form like stars, from colapse and fragmentation of a molecular cloud.

Key words. open clusters and associations: individual: Taurus – stars: brown dwarfs

1. Introduction

Brown dwarfs, objects unable to fuse hydrogen in an stable manner (i.e., with masses below at about 0.072 $M_{\odot}$, Baraffe et al. 1998), pose an important problem to the theory of stellar formation. Several formation mechanisms have been proposed, including formation like a star (from collapse and fragmentation of a molecular cloud, Padoan P., & Nordlund 2004) to a planet-like process (from a circumstellar disk) or as stellar “embryos”, ejected from multiple systems before they are able to accrete enough matter (Reipurth & Clarke 2001; Bate et al. 2002). These proposed mechanisms have different implication in their formation, their evolution and their properties. In particular, if brown dwarfs are created like stars, it seems that they should go through an phase of active accretion from a circum(sub)stellar disk, such as low mass stars do (Shu et al. 1987). Actually, since the last couple of years, different groups have presented indirect and direct evidences of active accretion in a handful of young brown dwarfs belonging to several nearby star forming regions (SFR), open clusters and moving groups (Fernández & Comerón 2001; Muench et al. 2001; Natta & Testi 2001; Natta et al. 2001, 2002; Testi et al. 2002; Jayawardhana et al. 2002ab, 2003ab; Muzerolle et al. 2003; Barrado y Navascués et al. 2002, 2003, 2004; Barrado y Navascués & Martín 2003; Mohanty & Basri 2003; Mohanty, Jayawardhana & Barrado y Navascués 2003; Comerón et al. 2003)

In this paper, we enlarge the sample by collecting high resolution spectroscopy of three proposed members of the Taurus-Auriga SFR, located at 140 pc and about 1-3 Myr (for an update on Taurus, see Luhman et al. 2003 and references therein).

2. Observations

Our Taurus targets were selected from Briceño et al. (2002). In that paper, a new sample of nine mid- to late-M candidate members were presented, based on I*c* and *z*' photometry (plus 2MASS near IR data) and low resolution spectroscopy. We have collected high resolution spectra of a third of them –the high mass brown dwarfs, whose spectral type is between M5.75 and M7.5– with the Magellan I 6.5m telescope and the MIKE echelle spectrograph on 2002, Dec 11-14th. Although three objects are a small number, they represent a significant fraction of the high mass brown dwarfs belonging to this association discovered so far (about 12 in the quoted spectral range). Therefore, they can provide some hints about their formation mechanism.

Additional details about the observations can be found in Barrado y Navascués, Stauffer & Jayawardhana (2004), where we analyze a sample of very low mass stars and brown dwarfs belonging to the $\sim$5 Myr cluster associated to the λ Orionis star. In order to optimize the signal-to-noise, we binned the data during the read-out to two by two pixels in the spatial and the spectral direction, respectively, yielding a spectral resolution of R=25,000 ($\sim$0.25 Å), with a 0.75 arcsec slit. The spectral range of our spectra is 4500–7250 Å.

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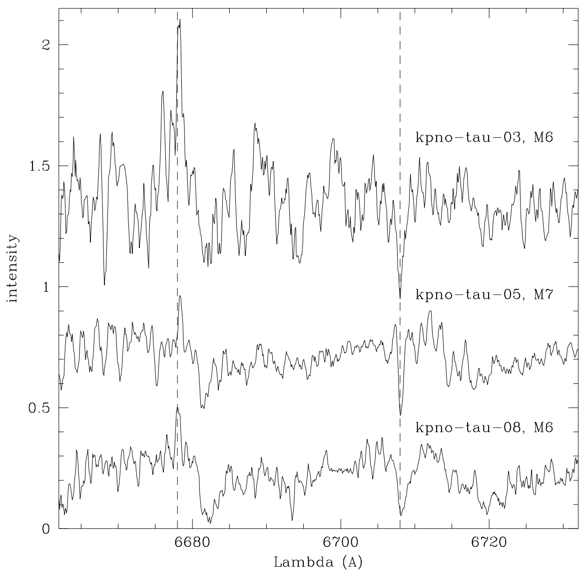

Fig. 1. Spectra around HeI6678 Å and LiI6707.8 Å.

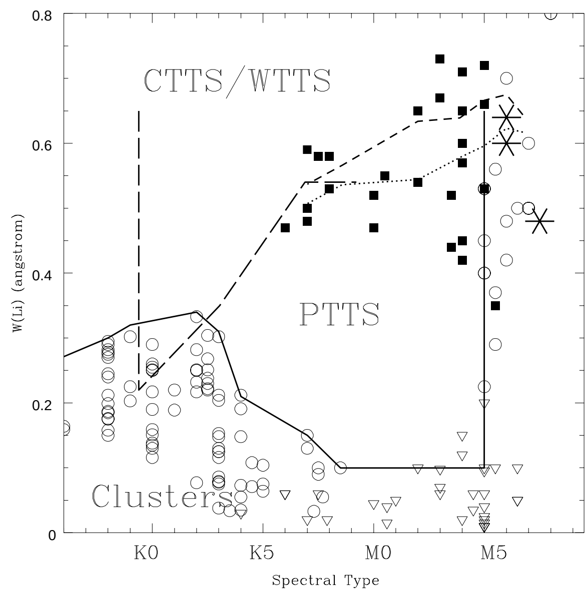

Fig. 2. Lithium equivalent width versus the spectral type. The solid line corresponds to the upper envelope of the values measured in young open clusters. The long-dashed line delimits the areas for weak-line and post-T Tauri stars (adapted from Martín 1997 and Martín & Magazzù 1999). Short-dashed and dotted lines correspond to the cosmic abundances –A(Li)=3.1– from gravities of Logg=4.5 and 4.0, respectively (curves of growth from Zapatero Osorio et al. 2002). All Pleiades and IC2391 members with measured lithium equivalent width are shown as open circles and triangles –upper limits–. Note the lithium depletion boundary at ∼M5.5. Sigma Orionis low mass stars and brown dwarfs appear as solid squares (Zapatero Osorio et al. 2002). The big asterisks represent KPNO-Tau-3, 5 and 8.

3. Analysis and Discussion

3.1. Spectral types

Spectral types were derived by comparing with several spectral templates, by using the order around 7050 Å, corresponding to a TiO band, following Mohanty et al. (2004), since this range is very sensitive to effective temperature. Errors can be estimated as half a subclass. Our values are very close to those obtained by Briceño et al. (2002) from low resolution spectra (see Table 1).

3.2. On the lithium abundance, age, and mass

We have detected lithium 6707.8 Å in two out of the three targets (KPNO-Tau-05 and KPNO-Tau-08, Figure 1). The spectrum of KPNO-Tau-03 has worse quality. With some caveats, the visual inspection indicates that this feature is also present. Note that Briceño et al. (2002) states that they detected lithium with their low resolution spectrum (at higher signal-to-noise ratio). This element is easily destroyed in the stellar interior, being its surface abundance dependent on mass and age (as well as other second order parameters). In fact, brown dwarfs which are more massive than about 0.060 $M_\odot$ do deplete lithium in a time scale of few tens of million years (D'Antona & Mazzitelli 1994; Burrows et al. 1997; Baraffe et al. 1998). The Taurus-Auriga complex has an age between 1 and 3 Myr. Since our three candidate members have spectral types between M6 and M7, they should have masses equal or larger than 0.06 $M_\odot$, according to Baraffe et al. (1998). Therefore, the detection of this alkali clearly indicates that these objects are in the pre-Main Sequence (PMS). Moreover, from the statistical point of view, the likelihood of having three late-M, PMS interloper whose spectral and photometric properties coincide with the Taurus sequence is negligible. Therefore, we have to conclude that they, indeed, belong to the association.

Figure 2 displays values of the lithium equivalent width (W) measured for our targets (large asterisks), pre-main sequence members of the ∼5 Myr Sigma Orionis cluster (Zapatero Osorio et al. 2002, solid squares), and stellar and substellar members of IC2391 –53 Myr– and the Pleiades –125 Myr– from Barrado y Navascués et al. (1999, 2004), Soderblom et al. (1993), García-López et al. (1994), Jones et al. 1996, Stauffer et al. (1998) and Jeffries et al. (1999). The solid line describe the maximum W(Li) measured in cluster stars. The long-dashed curve is an update version of the criterion used by Martín (1997) and Martín & Magazzù (1999) to distinguish between Weak-line and post- TTauri stars. Finally, the dotted and short dashed lines correspond to the Zapatero Osorio et al. (2002) curves of growth for Log g=4.0 and 4.5 and an abundance of A(Li)=3.1 (i.e., cosmic abundance). We have labeled in the plot different sections. The W(Li) for KPNO-Tau-5 is lower than the measured values in the other two Taurus objects. This fact might be due

to the presence of optical veiling, about r(6700)∼0.2, although we do not think this is the case. On one hand, no other sign of accretion has been found in this object (see next section). Moreover, this equivalent width is compatible with the dispersion found in Sigma Orionis and the –undepleted- values characteristic of cluster brown dwarfs. For the other two objects, no veiling seems to be present either. In the lithium equivalent width dispersion is real both in Taurus and Sigma Orionis cluster (the same effect is present in the Lambda Orionis association, Barrado y Navascués, Stauffer & Jayawardhana 2004), it might imply diferences in the surface abundances due to additional mixing mechanisms in the stellar and substellar interior, different to pure convection (such as those proposed in solar mass stars), differences in the structure due to different stellar and substellar parameters (such as fast rotation in the case of pre-Main sequence stars, Martín & Claret 1996), or to induced effects related to activity and/or rotation over the spectral feature itself or the surrounding continuum (see the discusion in Barrado y Navascués et al. 2001 and references therein).

As a summary, based on these data, mainly from the detection of lithium and accretion when present (see next section), we can conclude that these three objects are young and, indeed, belong to the Taurus region. In the case of KPNO-Tau-5, due to its spectral type (M7) its substellar nature is well established. The other two are located at the substellar borderline and their nature is not so firmly established due to uncertainties in the models and the spectral type determination.

Once membership to the stellar association has been proved, we have derived the bolometric magnitudes from Ic and Ks, the distance modulus $(m-M)_0$=5.731 (140 pc, Kenyon, Dobrzycka & Hartmann 1994), the reddening derived by Briceño et al. (2002) and the bolometric corrections by Comerón et al. (2000) and Tinney et al. (1993) for these two bands (Ic and Ks, respectively). Masses were computed based on models by Baraffe et al. (1998). Effective temperatures were obtained using several scales, namely Luhman (1999) for intermediate gravity and Leggett (2000, 2001). All the measured and derived values are listed in Table 1.

Figure 3 displays a HR diagram. The isochrones and evolutionary tracks –solid and dashed lines, respectively– are from Baraffe et al. (1998). Asterisks and open stars correspond to bolometric luminosities obtained from Ic and Ks, respectively. For this particular diagram, we made use of the effective temperature scale by Luhman (1999). Other temperature scales, such as that from Leggett et al. (2001), would shift the location of these three objects (two of them are almost on top of each other, the small shift in Teff is arbitrary) to the right hand-side, making them younger and less massive. Note, however, that Luhman' scale has been tunned specifically for the model we are using here. In any case, regardless the election of models (alternative models are, for instance, Burrows et al. 1997; D'Antona & Mazzitelli 1994, 1997, 1998; Chabrier et al. 2000; Baraffe et al. 2002), bolometric corrections and effective temperature scale, these members are at or below the substellar frontier and have an age of about 3 Myr.

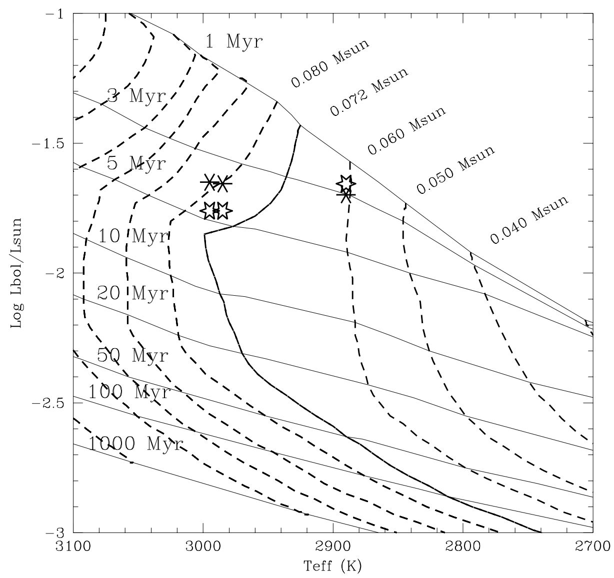

Fig. 3. HR diagram of KPNO-Tau-3 and 8 (on top of each other) and KPNO-Tau-5. The values represented by asterisks and open stars were derived from Ic and Ks magnitudes, respectively.

3.3. Near infrared photometry, Hα emission and accretion

None of our three targets seems to have neither the presence of forbidden lines, characteristics of outflows, nor near infrared infrared excesses, coming from an accretion disk. Figure 4 compares the colors $(Ic-J)$ and $(H-Ks)$, and includes the loci for dwarfs –Bessell & Brett 1988; Kirkpatrick et al. 2000; Leggett et al. 2001)– and Classical TTauri stars (Meyer et al. 1997, Barrado y Navascués et al. 2003) and Classical TTauri stars from Orion (Herbig & Bell 1988). As can be seen, the Taurus objects have photometric properties –data from 2MASS– similar to those MS stars of similar spectral type and, as stated in the previous paragraph, no near IR excess is seen. This fact, by itself, cannot prove or disprove the presence of a circum(sub)stellar disk, since a hole can be present or the disk temperature can be very cold. Moreover, the IR excess might depend on the orientation of the disk. See, for example, the case of LS-RCrA 1, M6.5 brown dwarf belonging to RCrA dark cloud (Barrado y Navascués, Mohanty & Jayawardhana 2004). Additional observations and longer wavelengths –more sensitive to cooler disks- both from ground-based telescopes and space-borne instruments such as those in Spitzer Space Telescope, can help to shed some light in this issue.

We have detected and measured Hα in emission for these three objects. The profiles of this feature are dis-

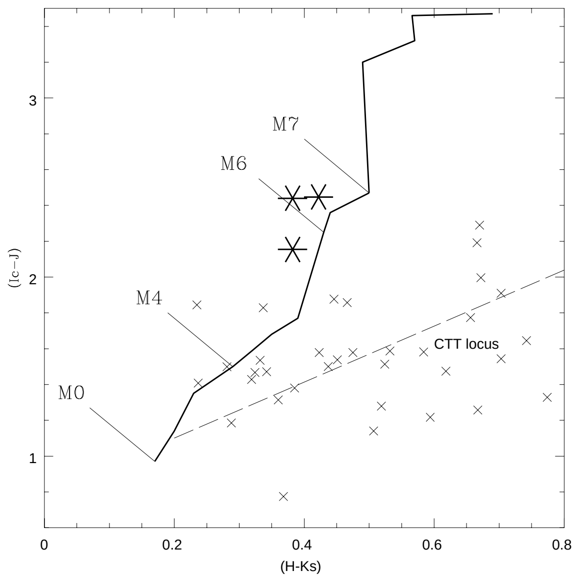

Fig. 4. Color-color diagrams. The position of the Taurus BD candidates are indicated with large asterisks. Crosses indicate the position of classical TTauri stars belonging to Orion stellar population (Herbig & Bell 1988). The thick-solid and dashed lines correspond to the locii of the main sequence stars (from Bessell & Brett 1988; Kirkpatrick et al. 2000; Leggett et al. 2001) and CTT stars (Meyer et al. 1997, Barrado y Navascués et al. 2003), respectively.

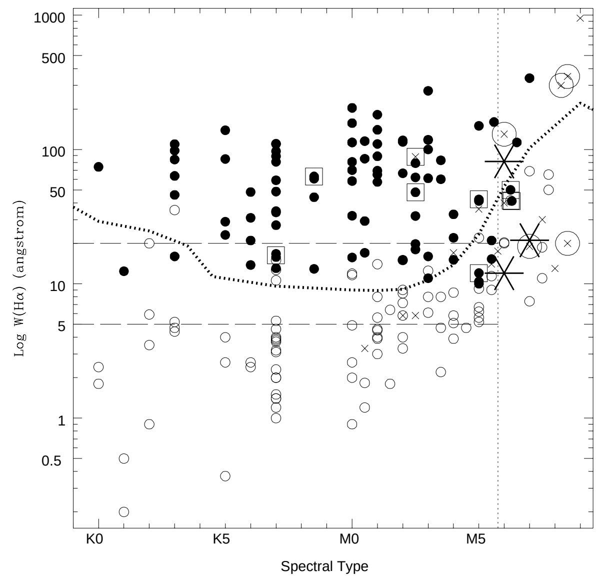

Fig. 6. Hα equivalent widths for members of the Taurus SFR. Solid and open circles correspond to Classical and TTauri stars. Objects with no classification are shown as crosses. Large open circles or square represent objects with mid-IR excesses and forbidden lines, respectively. The three objects studied here are displayed as large asterisks. The dotted, bold curve is the saturation criterion, whereas two previously proposed criteria (5 and 20 Å) to separate CTTS and WTTS are included as long-dashed, thin horizontal segments. The vertical dotted segment denotes the location of the substellar frontier.

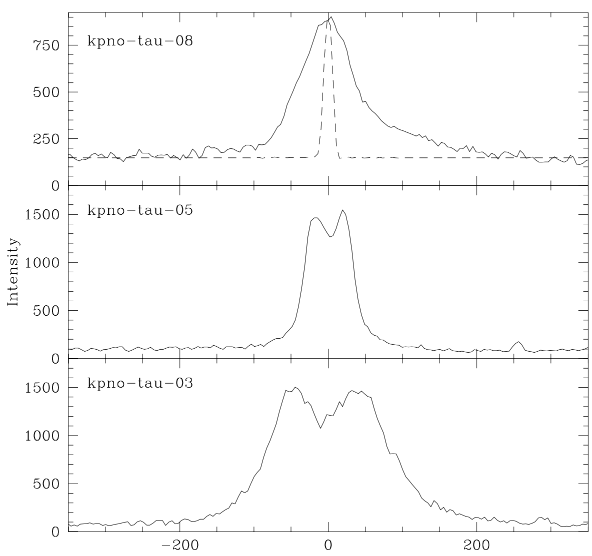

Fig. 5. Hα profiles. The instrumental profile is included as a dashed line (top spectrum).

played in Figure 5. Note the possible asymmetry in KPNO-Tau-8, the double peak in KPNO-Tau-5 and KPNO-Tau-3, and the width of the line (310 km/s), typical of accreting brown dwarfs (White & Basri 2003; Jayawardhana et al. 2003). In fact, this last object is above the criterion defined by Barrado y Navascués & Martín (2003) which discriminate between accreting and non accreting objects, as Figure 6 clearly indicates. We note, however, that this criterion depends on low resolution spectroscopy, which normally yields larger equivalent widths compared with higher resolution data. In this diagram, we have included Classical and Weak-line TTauri stars belonging to Taurus as solid and open circles. Members without classification are included as crosses. Our three targets appear as large asterisks. Overlapping squares and big circles denote those members with forbidden emission lines and near-infrared excesses, respectively. This large W(Hα) agree with the fact that we also detect HeI6678 Å, another accretor indicator (see Figure 1).

Active accretion in at least one Taurus member whose mass is close or below the substellar limit is important for several reasons. First, although the sample studied in this paper is very small, it suggests that a significant fraction of the very low mass stars and high mass brown dwarfs might harbor an accretion disk. Second, the new data amass additional evidence for accretion in the substellar domain. To the best of our knowledge, there are only three papers dealing with high resolution spectra in Taurus brown dwarfs (White & Basri 2003; Muzerolle et al. 2003; and Jayawardhana et al. 2003). The first work

found three accretors in a sample of ten very low mass stars and brown dwarfs, although the less massive, a M6.5 (GM Tau), has a mass just above the substellar limit. The second paper includes four objects whose spectral type is M6 or M7. None of them seem to undergo active accretion based on the width of Hα, although the authors claim that one of them, namely MHO-5, is accreting based on the detection of forbidden lines of oxygen at 6300 and 6363 Å and CaII IRT. Moreover, three out of the four were observed at moderate resolution, including MHO-5 (R$\sim$8000). Regarding the later study, the four M7-M7.75 brown dwarfs discussed there, with masses down to 0.05 $M_\odot$ (again, using Baraffe et al. 1998 models), do not show accretion either. Muzerolle et al. (2003) also analyzed seven Taurus members whose spectral types are M4.75–M5.75 (just above or at the substellar borderline). Three out of these seven are accreting, based on the width of Hα and other spectral indicators. Therefore, up to date, our study presents the only brown dwarf belonging to Taurus (kpno-tau-03), at the substellar limit, which has been proved to be accreting.

In conjunction with the studies quoted in the previous paragraph, our results indicate that about 10% of the Taurus brown dwarfs (one out of 11) is actively accreting. This fraction is much smaller than the accretion occurrence in low mass stars in the association or the estimate for the substellar domain (about 50%) based purely on the strength of Hα measured in low resolution spectra (Barrado y Navascués & Martín 2003). The statistical criterion defined in this last work is based on the saturation of the activity, as measured in several young open clusters (namely IC2391, Alpha Per and the Pleiades, with ages ranging from about 50 to 125 Myr). The discrepancy in the fraction of accreting brown dwarfs might imply that there is an additional source of flux in Hα line or that the accreting criterion based on the Hα width at 10% of the maximum intensity, as defined by Jayawardhana et al. (2003), i.e. 200 km/s, is too restrictive.

The detection of accretion in substellar objects indicates that they undergo a phase similar to Classical TTauri stars (for a review, see Bertout 1989 or Appenzeller & Mundt 1989). A handful of other brown dwarfs belonging to other young stellar association, with ages ranging from 1 to 10 Myr, have been observed with high resolution spectroscopy and the presence of accretion confirmed. In at least one, LS-RCrA 1 (Fernández & Comerón 2001; Barrado y Navascués, Mohanty & Jayawardhana 2004), outflows have been seen, by means of the detection of intense, narrow forbidden lines. In a previous paper we have named them Classical TTauri substellar analogs (CTTSA). Therefore, we can conclude, at least in the case of high mass brown dwarfs (Mas$\sim$0.072–0.04 $M_\odot$), that they are formed as low mass stars, by fragmentation and collapse of the original molecular cloud. Of course, additional studies are needed to confirm this preliminary conclusion, in particular high resolution imaging in the near and mid- infrared, as well as in the optical. Narrow band imaging might show whether these objects present outflows similar to those observed in some Classical TTauri stars.

4. Summary

We have collected high resolution spectroscopy for the members of the Taurus-Auriga SFR. They have M6-M7 spectral types with moderate to intense Hα emission, with profiles that, at least in one case, can be classified as typical of an accretor. We detect lithium too, which indicate that they are in the pre-main sequence (more strictly, the equivalent width imposes a maximum age of about 30 Myr, based on Baraffe et al. 1998). Moreover, at least one, possibly two of them, are accreting material, as shown by the Hα profile, providing an additional, stronger constrain to the age, about 10 Myr. Therefore, a minimum of a10% (one out of eleven) of the high mass brown dwarfs known in the cluster show accretion (i.e., circumsubstelalr disks). Note, however, that these objects do not have near-infrared excess and do not show forbidden lines, although HeI6678 Å, another signpost of accretion, appears in the spectrum of one of them, possibly in the other two. Since the likelihood of having a stellar association younger than 30 Myr in the same line-of-sight as Taurus, we can safely conclude that these objects belong to this SFR. Based on the new spectral types and magnitudes in the optical and infrared, we derived masses around the substellar limits and an age close to 3 Myr. Finally, the detection of accretion in the substellar domain provides another clue about the formation mechanism of high mass brown dwarfs, suggesting that they form as stars, by fragmentation and collapse of a molecular cloud.

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Table 1. Data for the three Taurus low mass members.

	KPNO-Tau		
	#3	#5	#8
Ic	15.77	15.08	15.10
J	13.323±0.022	12.640±0.024	12.946±0.022
H	12.501±0.022	11.918±0.024	12.367±0.021
Ks	12.079±0.021	11.536±0.018	11.985±0.022
Sp.Type	M6 (M6)	M7 (M7.5)	M6 (M5.75)
Width Hα (km/s)	310	125	240[1]
W(Hα) (Å)	81.4±5.7 (130)	21.1±0.9 (30)	12.0±1.0 (17.5)
W(HeI6678) (Å)	3.5: (6.5)	0.2:	0.2:
W(Li) (Å)	0.60 (Yes)	0.48	0.78
Log Lum(bol)/L$_\odot$	-1.66/-1.76[2]	-1.70/-1.66[2]	-1.65/-1.76[2]
Mass (M$_\odot$)	0.07[3]	0.06	0.07[3]
Log L(Hα)/L(bol)	-2.87	-3.70	-3.70
Teff (Luhman 1999)	2990	2890	2990

Values in parenthesis –from low resolution spectroscopy– from Briceño et al. (2002). A double colon implies a large uncertainty in the measurement.

[1] 180 km/s without the asymmetry.

[2] From Ic and Ks, respectively.

[3] 0.08 M$_\odot$ from the HR diagram. The listed values are from Ic and Baraffe et al. (1998)

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